

Strength of Materials Subjected to Shear at High Temperatures¹



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This paper treats of an experimental program which is basically fundamental in the study of creep. Uniformly pure shear is produced in a thin tubular specimen submitted to twist, whereas the usual method employs a solid bar in tension. This torsion form of test permits of greater accuracy in the measurement of creep and provides the simplest stress condition, besides offering other decided advantages.

Since the work in twist represents virtually a pioneer attack, it has been necessary to develop practically from the beginning each phase of the investigation. The type of specimen, apparatus for the creep tests, including the measuring instruments, and experimental technique are described.

The experiments have been of three kinds: (1) Room-temperature tests were first made to determine the usual physical properties in torsion and in tension; (2) at various temperatures short-duration tests were made to learn the effect of different rates of loading, the modulus of elasticity in shear, and the ultimate strength in shear; (3) at 400 deg. cent. and 500 deg. cent. several creep tests in shear of relatively long duration were conducted. An accelerated method of making creep tests has been devised. In addition several special problems were investigated such as a study of the increase of the yield point by creep and the restoration of the original yield point by annealing, the effect of vibrations which included a continuous record of creep, and the effect of temperature fluctuations.

INTRODUCTION

1 STATEMENT OF THE PROBLEM



THE outward manifestations of creep are now generally recognized. In cases of commercial importance, metal which is subjected to the simultaneous action of stress and high temperature undergoes continual distortion. A large number of investigators of creep and others interested in the problem, particularly in the United States and Europe, have contributed considerable information on the practical significance of creep and data applicable for purposes

of design of equipment which operates under conditions where creep obtains. So satisfactorily has this part of the subject of creep been covered that it appears neither necessary nor

possible to devote more than an occasional sentence to a review.

It is felt that the broad subject of creep deserves more fundamental study. The manner in which creep occurs is too interesting a question to remain unexplained. Very low rates of creep are required to furnish a more complete picture of the problem. The immediate investigation is believed to approach more closely than is possible by tension methods a situation which permits this fundamental research.

A large amount of work has been done to determine creep characteristics of metals in tension. In the present study the attack is different—creep in uniformly pure shear is produced by using a tubular specimen in twist.

In this study there have been developed the machines, type of specimen, and the measuring instruments which give more refined readings than are known to have been obtained in any other laboratory. The experimental technique has also been developed.

Some results have been obtained for giving the characteristics of medium-carbon steel at three temperatures, namely, 400, 450, and 500 deg. cent., and in addition some work has been accomplished at ordinary temperatures. Only one material has been used in the tests, since it was desired to prepare as complete information for comparative purposes as was possible.

The experimental work has been of three kinds: (1) A number of tests have been performed at room temperature to learn the usual physical properties of the material; (2) a series of short-duration tests at high temperature were made in order to establish the more important physical properties under such conditions and to provide some preliminary tests which might be useful in predicting the behavior of the material in creep; and (3) a few long-duration creep tests were run to study the material when it was exposed to service conditions of high temperature and stress over some time. Also several special problems have received attention which deal with practical considerations relating to the matter of creep.

2 TORSION VS. TENSION

Torsion methods of studying the problem of creep present certain advantages over those in tension. It is due to these and the basic value of creep results in general that the present project has been undertaken and developed.

As a result of temperature fluctuations of the specimen during a test, the effect upon strain measurements is much more serious in the case of tension than in torsion. Due to a thermal change of 1 deg. cent. on the length alone, the effect upon strain readings in tension tests is 1.2×10^{-6} inches per inch of length, whereas

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors, and not those of the Society.

in torsion the geometric changes due to temperature are of only very slight consequence. Consideration of all effects upon measurements in torsion is given in a discussion in Section V, Article 3. This situation immediately presents a distinct advantage of torsion methods over tension.

Means of obtaining very fine measurements of strain in torsion are simpler than in tension. It is possible to combine mechanical and optical levers favorably so as to detect very refined values of strains due to torsion.

In torsion a moment of constant magnitude is easily designed to act automatically on the specimen throughout the experiment. The usual tension creep apparatus requires that the load beam be readjusted to maintain a uniform force on the specimen during elongation.

The maximum-shear theory is usually selected as the basis of design of machine parts, so that information concerning the shearing stress of ductile material such as steel is of practical importance. It is generally accepted that deformation of ductile material, such as steel, takes place due to gliding on the plane of maximum shear.

Experiments in uniformly pure shear provide the simplest stress condition and therefore allow the most favorable situation

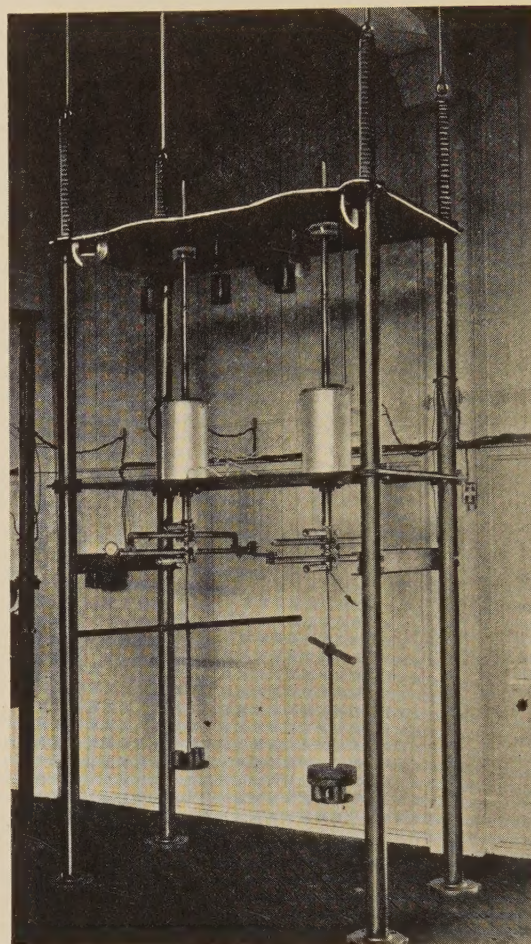


FIG. 2 NOS. 2 AND 3 TORSION MACHINES

for making a study of such a problem as is offered by creep. Tension methods produce a more complicated stress condition on the plane of maximum shear, since normal tensile forces are also present.

I—APPARATUS AND SPECIMENS

1 TORSION MACHINES

In the design of the apparatus for the torsion investigation, a number of requirements were imposed. The specimen was to be tubular, held rigidly at one end, and twisted free from bending or longitudinal pressure at the other end with a known moment which remained constant during angular deformation of the specimen. Friction was to be held to a minimum. The specimen was to be contained in a furnace and maintained at constant temperature. Some provision had to be made for accurately measuring shear strain.

A diagrammatic sketch of the essential features of the torsion machine is given in Fig. 1. Two of the new machines built integral in the same frame are shown in Fig. 2. Discussion will be directed toward the design of the improved apparatus of the last two units. The fact that the torsion specimen was tubular established the form of the slotted adapters (a), Fig. 1. The end which resisted rotation was made a splined shaft (b) to allow for axial adjustment in inserting and removing the specimen. The other end was connected to a large, light-weight aluminum disk (h) on the circumference of which two fine music wires (g) produced a couple. These wires passed over pulleys (f) of relatively large diameters and were fastened

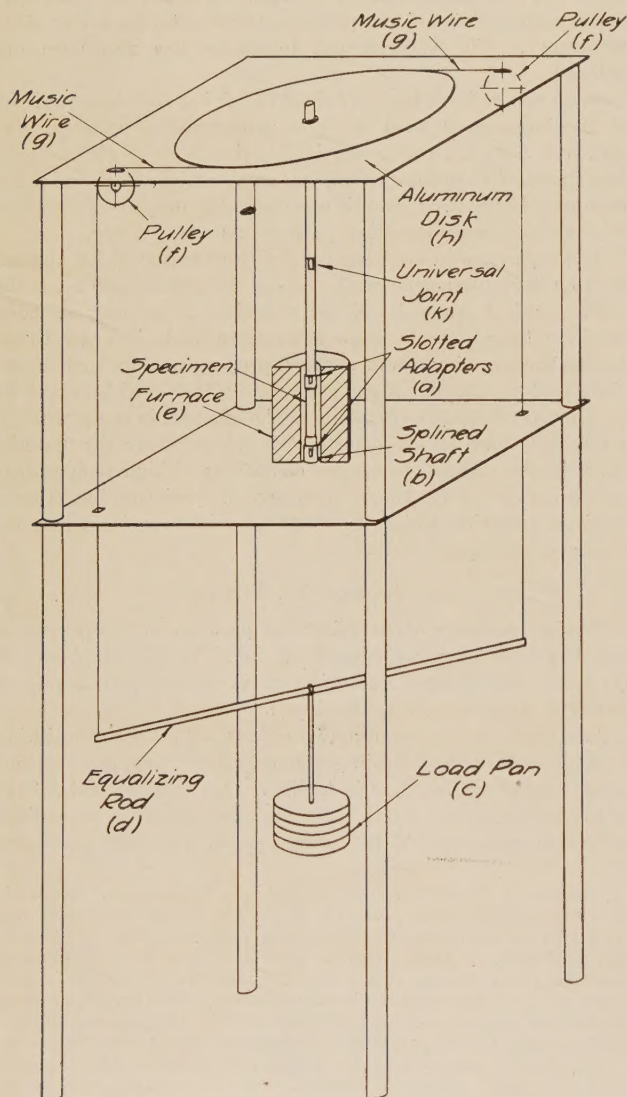


FIG. 1 DIAGRAMMATIC SKETCH OF TORSION APPARATUS

to both ends of an equalizing rod (d), to the center of which a platform (c) was attached for applying loads. The large disk and pulleys were mounted on ball bearings to reduce the friction. Between the rigid end and the aluminum disk which furnished the moment, a universal joint (k) was supplied in the shaft to eliminate the possibility of bending action upon the specimen.

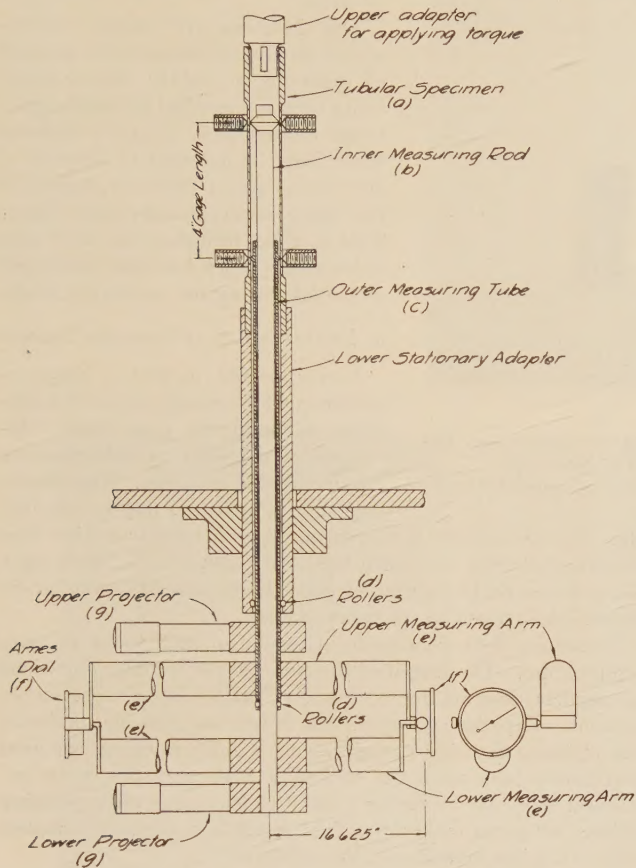


FIG. 3 SHEAR-STRAIN MEASURING DEVICES

Some play between the specimen and the adapters allowed axial thermal expansion without causing longitudinal pressures.

Since the furnace (e) surrounded the specimen, part of the shear-strain-measuring apparatus had necessarily to be within the heated zone. It was decided that it was best to select a vertical design of machine in order to permit these measuring devices to hang downward and thereby avoid bending and general distortion due to the heat. Detailed descriptions of the instruments and furnaces are given in the following articles.

A salt or lead bath to protect the specimen from excessive oxidation could be used very easily with this apparatus. The design of the machine is favorable to this arrangement.

2 STRAIN-MEASURING INSTRUMENTS

Exceeding simplicity and accuracy have been embodied in the principle and design of the devices for measuring angular deformations of the specimen. It was necessary to devise means of measuring the relative angular motion of two cross-sections of the specimen. Several methods have been developed, and during various stages of the same test, each, depending upon the rate of movement and the degree of sensitivity demanded, may be employed. The systems are mechanical, optical, or combinations of the two. The different methods that have been developed number four and will be discussed in the order of the accuracy which they are capable of obtaining.

The gage length which has been arbitrarily selected as 4 in. is constant in all experiments where strain is measured. A concentric rod and tube, accordingly, are clamped by suitable means inside the specimen. A sectional drawing which illustrates the method of securing the rod and tube at the gage points and the attachment of the strain-measuring instruments is given in Fig. 3. The relative angular movement between this rod and tube describes the shear strain of the 4-in. portion of the specimen (a) which is under investigation. To the rod (b) and tube (c) one or more of the devices (f, g) for measuring the strain are attached. Rollers (d) are provided to steady the rod and tube at the lower ends.

The simplest method of measuring shear strain which is employed throughout the entire test consists of a pair of projectors (g), one each attached to the rod and tube, equipped to cast a sharp vertical shadow on a curved graduated scale. The projectors may be readily seen in Figs. 4 and 5. This optical lever is used in connection with either of two scales of 96 in. and 174 in. radius, respectively. The smallest reading that can be observed on the scales is 0.01 in., which corresponds to angles of 1.04×10^{-4} and 5.75×10^{-5} radians, respectively. The shear strain which can be measured is then 1.29×10^{-5} and 7.09×10^{-6} in order. Although this method constitutes the least refined means of measuring the strain, the minimum rate of creep, for example, over a 12-hour period, may be read to 1.07×10^{-6} for the 96-in. and 5.91×10^{-7} for the 174-in.-radius scale, strain

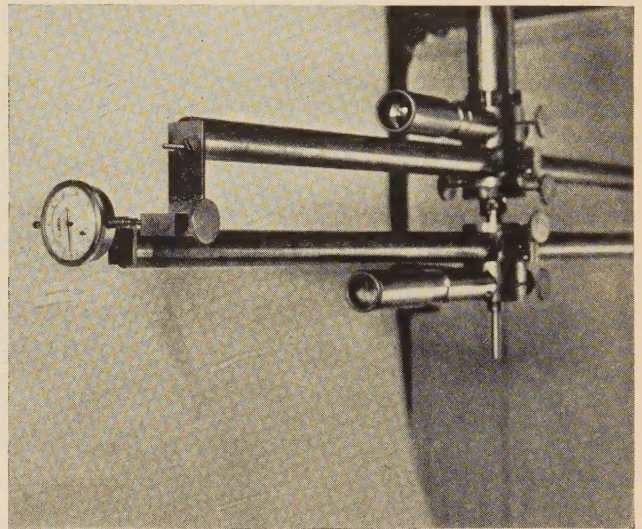


FIG. 4 AMES DIALS AND PROJECTOR ATTACHMENTS

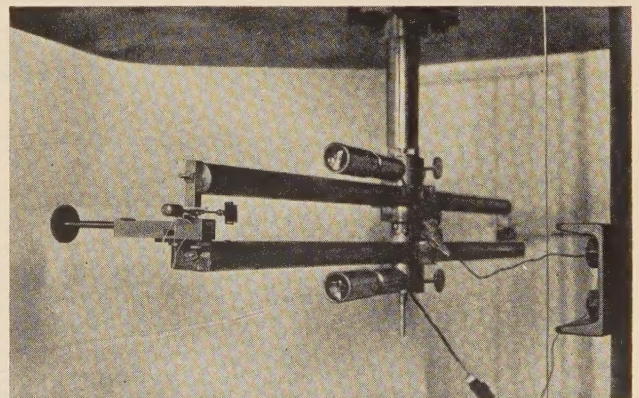


FIG. 5 MARTENS MIRRORS AND PROJECTOR ATTACHMENTS

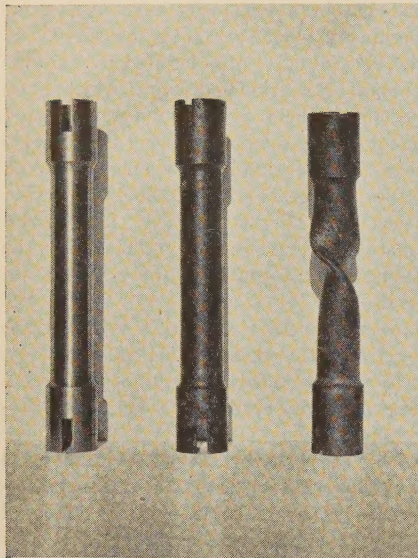


FIG. 6 TUBULAR SPECIMENS FOR ELASTIC AND CREEP TESTS IN TORSION

[(a) Unstressed tube. (b) After creep test. (c) After buckling failure.]

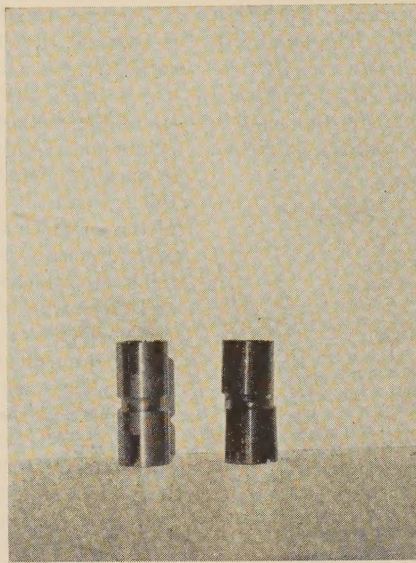


FIG. 7 SHORT-LENGTH SPECIMENS FOR ULTIMATE SHEARING STRENGTH

[(a) Unstressed tube. (b) After shear failure.]

per hour. When rates are so low that more refined devices must be resorted to, this projector method furnishes a check and the amount of the total deflection.

The other three more delicate methods of measuring the strain take advantage of a mechanical-lever mechanism in addition to the sensitivity provided by the various strain instruments themselves. Arms (e) in Fig. 3 are fastened rigidly to the rod and to the tube. Various types of instruments (f) are mounted which measure the relative linear displacement of the outer ends. It is assumed, at the comparatively large radius at which the instruments are located, that for small angular movements the arc and chord are equal. Linear-strain-measuring devices serve to indicate these movements.

In the first of these cases Ames dials (f), which will permit of a minimum reading of $1/10,000$ of an inch, are employed. Rates of creep with readings at 12-hour intervals are accurately read to some 6.19×10^{-8} strain per hour. This method gives very satisfactory results for rates of creep within this range. Fig. 4 is a photograph which shows the Ames dials being employed for measuring the shear strain.

The Huggenberger tensometers, which are more widely used in European laboratories than in this country, permit the measurement of linear displacements of the order of $1/100,000$ of an inch. These instruments consist essentially of a compound set of mechanical levers. The Huggenberger instruments are attached to the end of the arms (e, Fig. 3) in the same man-

ner as the Ames dials. It is seen that the accuracy obtained is about ten times as great as with the Ames dials. The minimum rate of creep is of the order of 5.15×10^{-9} strain per hour when the readings are made at 12-hour intervals.

The Martens-type mirror instruments, seen in Fig. 5, provide a method of obtaining a slightly greater sensitivity than is furnished by the Huggenberger tensometers. The rate of creep which can be detected is about 5×10^{-9} shear strain per hour, based on the same interval previously used. This method furnishes the most sensitive means which has been developed at the laboratory for measuring creep.

3 DEVELOPMENT OF SPECIMEN DESIGN

It was desired to find a shape of specimen which would approach a condition of uniformly pure shear. Obviously a solid shaft in twist presents an unfavorable situation. The phenomenon is complicated due to the fact

that the stresses are not uniform. A thin tubular section was therefore selected, for which the assumption can be made that stresses are evenly distributed over the cross-section, and their magnitude is based on the mean radius.

Numerous tests were made in torsion of such tubes at room temperature. The length of the thin section for determinations of angular deformation necessarily had to be of appreciable amount. Experience showed that it was not possible to obtain the ultimate shearing strength, since sudden buckling occurred and failure took place due to tension. Photographs of an unstressed tube, one following a creep test and one after buckling failure, are given in Fig. 6. This design was certainly adapted only to a stress somewhat below ultimate.

Since buckling was not observable in the least until the final

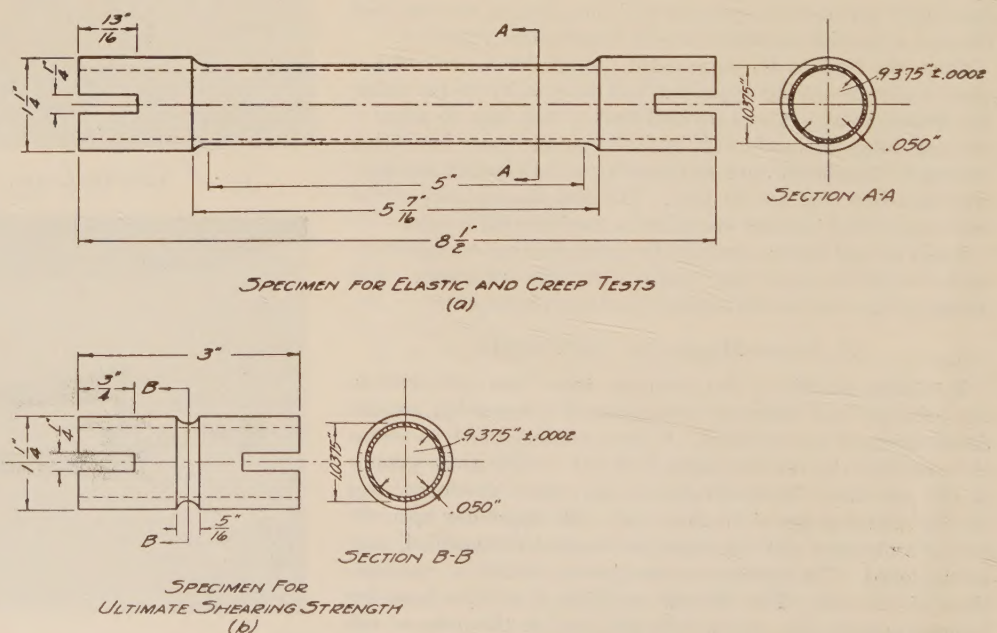


FIG. 8 TUBULAR SPECIMENS

stage of the test, observations of strain during the first part of the test, which was the important part for creep measurements, were not affected.

In order to get data for ultimate strength, the final design adopted was merely a rounded groove with a long radius at the bottom, a photograph of which is shown in Fig. 7 both before and after failure.

The two standard type specimens, then, which were employed throughout the torsion tests reported here, were of the design described in the above-mentioned development. The specimen which was used for the investigation of all elastic and creep-test determinations is shown in Fig. 8(a), while the design adopted for the few tests where ultimate strength was required is given in Fig. 8(b).

Later tests have indicated conclusively that no measurable buckling took place when the specimen chosen for creep tests was subjected in the usual experiments to shear stress over long periods of time.

II—MATERIAL

1 ROUGH STOCK

As much care as possible was exercised in the selection of

An analysis in the University laboratory showed the carbon content of the tubes to be 0.347 per cent, with a maximum variation of 0.001 between samples.

Upon receipt in the laboratory the tubes were cut to the length desired for the specimens and annealed in an electric furnace in an atmosphere of air. The annealing temperature in all cases was 900 deg. cent., which was maintained for a period of from fifteen to thirty minutes. The tubes were permitted to cool slowly in the furnace.

2 PRELIMINARY TESTS AT ROOM TEMPERATURE

It was desired to investigate the physical properties of the material in tension and in torsion at ordinary temperatures by the usual short-time methods. For the tension tests two types of specimens were used. Small rectangular strips were cut from the walls of both unannealed and annealed tubular stock and subjected to tension. From these tests it was decided that only annealed material would be used in subsequent experiments, since uniformity in results and a sharp yield point could be obtained only when the material was in the annealed condition. Tubular specimens, as the second type, were tested in tension also. The tube stock was turned down into the same essential form

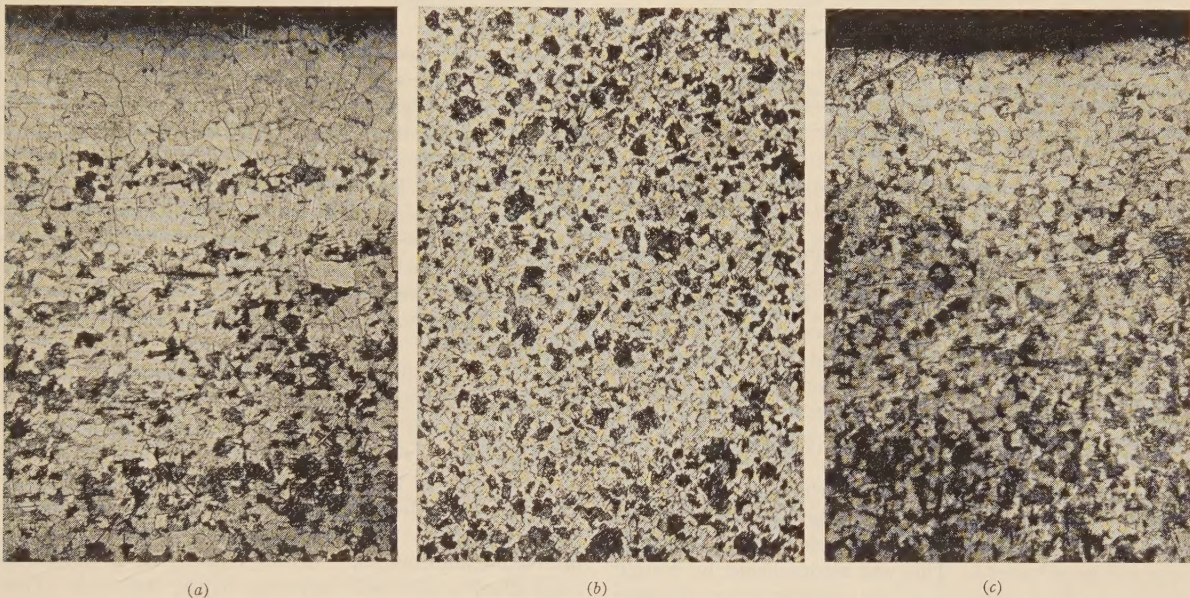


FIG. 9 PHOTOMICROGRAPHS OF MATERIAL

[(a) Highly decarburized inner surface. (b) Homogeneous interior structure. (c) Slightly decarburized outer surface.]

material for the program of experiments. It was desired to have a steel which exhibited usual physical properties and which at the same time was homogeneous. Since the finished specimens were to assume the form of a thin hollow cylinder, tubular stock was preferred. A medium-carbon seamless steel mechanical tubing was chosen.

This steel has properties which are well known at ordinary temperatures. The material was obtained in one lot sufficient for the entire investigation. The manufacturer's chemical analysis furnished the following:

TABLE 1 TENSION TESTS AT ROOM TEMPERATURE

Type of specimen	Condition	Mark No.	Prop. limit, lb. per sq. in.	Yield point, lb. per sq. in.	Tensile strength, lb. per sq. in.	Elongation, per cent	Red. of area, per cent	Modulus $E \times 10^6$, lb. per sq. in.
Strip	Unannealed	1	60,000	...	91,200	13	45	30.5
Strip	Annealed	3	40,700	40,700	72,300	36	48	28.9
Tube	Annealed	4	34,350	34,350	67,600	35.5	..	29.3

which was adopted for the torsion experiments, as seen in Fig. 8(a).

The magnitudes of proportional limit, yield point, ultimate tensile strength, elongation, reduction of area, and modulus were obtained for each specimen. In the case of the tubular form, all of these values were consistently lower than for the strip type. This was later attributed to the fact that there was a thin layer of decarburized material at the inner surface of the original tube stock which formed a larger proportion of the cross-section in the thin tubular specimen than in the thicker strip. Representative tension tests are reported in Table 1.

It was further decided to subject the material to metallographic examination. Sections at right angles to the axis of both

	Per cent
Carbon.....	0.34
Manganese.....	0.80
Phosphorus.....	0.02
Sulphur.....	0.03
Silicon.....	0.10

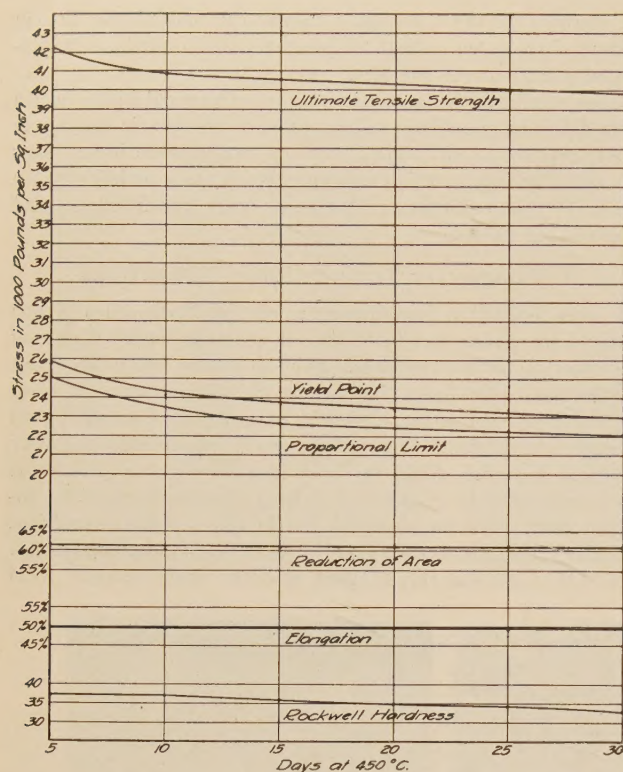


FIG. 10 MECHANICAL TESTS OF THIN STRIPS AT ROOM TEMPERATURE AFTER VARIOUS LENGTHS OF HEATING AT 450 DEG. CENT.

the strips and tubes were polished and photomicrographs prepared. As can be seen by referring to Fig. 9, the material throughout the cross-section is not homogeneous. Fig. 9(a) shows the structure of more than half of the thickness of the tube specimen. A large proportion is decarburized and consequently weaker than the interior material. A photomicrograph of a section of the strip showing the center is given in Fig. 9(b). This is the normal structure. Another sample was taken from the thick end at the grip of a tubular specimen. The outer surface, as may be seen in Fig. 9(c), is slightly decarburized.

From this study it was perceived that the tubular specimens must be redesigned so as to include only homogeneous material which was not decarburized. This was accomplished by merely increasing the internal diameter as well as the external diameter in order to maintain the same wall thickness of 0.050 in. The material, then, consisted wholly of the homogeneous structure shown in Fig. 9(b).

For the torsion tests at room temperature, annealed tubular specimens of two forms were used. To determine the elastic properties the original design described above was employed. In order to obtain the value of ultimate shearing strength a special type was devised of considerably shorter length and of reduced section. Details of this form of specimen and its development have been discussed in Section I, and reference in that connection may be made to Figs. 7 and 8(b).

Table 2 gives the characteristic data derived from the torsion tests at room temperature.

TABLE 2 TORSION TESTS AT ROOM TEMPERATURE

Type of specimen	Mark	Prop. limit, lb. per sq. in.	Yield point, lb. per sq. in.	Shearing strength, lb. per sq. in.	Modulus $G \times 10^6$, lb. per sq. in.
Long tube [Fig. 8(a)]	1	20,300	20,600		11.5
1/2-in. reduced section	31	....	....	57,300	....
1/4-in. reduced section	34	....	....	59,200	....
1/4-in. reduced section with fillets	35	....	....	63,600	....
Long tube with steel disks	29	....	....	57,800	....
Round groove [Fig. 8(b)]	71	....	....	65,870	11.5

The yield point in torsion for this annealed material was well defined. In the case of the specimen with only $1/32$ in. length of reduced section it is probable that the dimensions of the wall were not accurately known. The value of ultimate shearing strength obtained from No. 71 is considered reliable.

Bearing in mind that the reduced section of the tubes with the exception of No. 71 consisted to an appreciable extent of weaker decarburized material, we can relate the information of the tension and torsion tests. Comparing the values of yield point, the ratio obtained in uniformly pure shear to that in tension at ordinary temperatures assumes the value of approximately 0.6, which is in good agreement with the maximum-energy theory.

3 EFFECT OF LONG-TIME HEATING ON PHYSICAL PROPERTIES AT ROOM TEMPERATURE

It has been conjectured that steel subjected to the continued effect of high temperatures may undergo some structural change. This alone may produce differences in the physical properties, so that in creep tests it may be possible that the specimen becomes continually weaker—or perhaps stronger—under the single action of prolonged heating. Furthermore there is a possibility that long-time exposure to some temperatures at which creep tests are conducted results in decarbonization of the surfaces of the metal.

These questions were approached by investigating strips of steel $1/16$ in. thick and 1 in. in width, of $0.068 \pm 0.004C$ content. The strips were given an initial anneal at 900 deg. cent. and allowed to cool in the furnace. They were then heated for various lengths of time at 450 deg. cent. This temperature was arbitrarily selected. Two strips were heated for 5 days, two for 10 days, and so on through 30 days, so that twelve specimens were prepared. At the conclusion of the heating periods the strips were again allowed to cool slowly in the furnace.

After the heating, mechanical tests were made on the strips at room temperature to determine their hardness and tensile properties.

Although it is appreciated that the hardness of strips as thin as $1/16$ in. undoubtedly cannot be accurately determined by means of the method of the Rockwell machine,³ the $1/16$ -in.-diameter ball and 100-kg. weight were used to study the relative hardness of the strips. It was felt, however, that the consistency of the observed values for a given specimen and the reasonable qualitative agreement with the subsequent tension tests presented interesting information. It was found that prolonged heating resulted in a continual softening of the material. The curve for hardness is given in Fig. 10.

Each strip was tested in tension at ordinary temperatures. The general physical properties—proportional limit, yield point, ultimate tensile strength, breaking strength, reduction of area, and elongation—were determined. Again it is observed by further reference to Fig. 10 that the effect of heating was to weaken the steel, and that there is a material falling off in the magnitude of tensile strength, yield point, and proportional limit. The reduction of area and elongation appear to remain unchanged.

The results of this particular set of tests are offered as a qualitative indication only of what may obtain in situations where metal is subjected for long periods to high temperatures. More

experimental evidence is needed to establish convincing arguments concerning the problem.

³ G. A. Hankins, "Hardness Tests of Steel Strip," *Engineering* (London), vol. 130, 1930, p. 324.

III—SHORT-DURATION TESTS AT HIGH TEMPERATURES

1 PROBLEMS INVESTIGATED

All of the experiments at high temperature in twist where the tubular specimen was subjected for the major part of the test to a varying load and uniform temperature are for convenience discussed here under "Short-Duration Tests." Some of these single tests required as much time as two or three weeks, while others took only a few minutes.

Three types of problems were investigated: (1) the effect of various rates of loading; (2) the determination of modulus of elasticity in shear; and (3) the value of ultimate strength in shear. These tests were made at temperatures ranging up to 500 deg. cent.

2 EFFECT OF VARIOUS RATES OF LOADING

Prior to making the regular creep tests, a series of experiments at each of several selected temperatures was run to study the effect of the rate of application of the load and the behavior of the creep during the intervals between loading. The form of specimen is shown in Fig. 8(a). These tests were directly used to predict roughly what creep rates could be expected subsequently in the long-duration creep tests. It was felt that later a more accurate method of prediction could be discovered, based on these short-time tests.

The same general procedure of applying the load was followed in each of these experiments. A specimen was loaded with equal increments (always 10-lb. weights, which corresponded to about 1600 lb. per sq. in. shear stress, depending upon the exact measurements of the particular specimen) at definite intervals of time. These loading periods in each series were 1 minute, 1 hour, and 24 hours, and the tests repeated for 400, 450, and 500 deg. cent.

The results are given in the curves of Figs. 11, 12, and 13.

During the interval between the addition of the loads in the case of the one-day period, several observations of strain were made, as frequently as each two to four hours in the early stages after each loading, and the rates of creep determined. Fig. 14 shows representative curves obtained in this manner at 500 deg. cent. It was an interesting discovery to find that the logarithm of the rate over the last 12 hours of each 24-hour period plotted against the corresponding stress which was acting, resulted substantially in a straight line. It was further significant in the case of the tests at 400 deg. cent. that this line paralleled the one which represented the minimum rate obtained in long-time creep tests. Such a comparison may be made by reference to the broken-line curves of Fig. 18 for 400 deg. cent. and Fig. 19 for 500 deg. cent. It is believed that some relationship may exist between the two curves so that predictions of minimum rate can be made on the basis of knowledge gained from such short-time tests and only a few regular creep tests.

The method of measuring angular deformations in all of these short-time tests was by the projectors and 96-in.-radius scale. The various devices for strain-measurement determinations have been described in Section I.

3 MODULUS OF ELASTICITY IN SHEAR

Modulus of elasticity in shear of the material at various temperatures from normal to 500 deg. cent. was determined, employing the specimen in Fig. 8(a). A curve is plotted from the resulting data in Fig. 15. This is in close agreement with studies in tension by McVetty and Mochel⁴ on similar

⁴ P. A. McVetty and N. L. Mochel, "The Tensile Properties of Stainless Iron and Other Alloys at Elevated Temperatures," *Trans. A.S.S.T.*, vol. II (1927), pp. 82, 100.

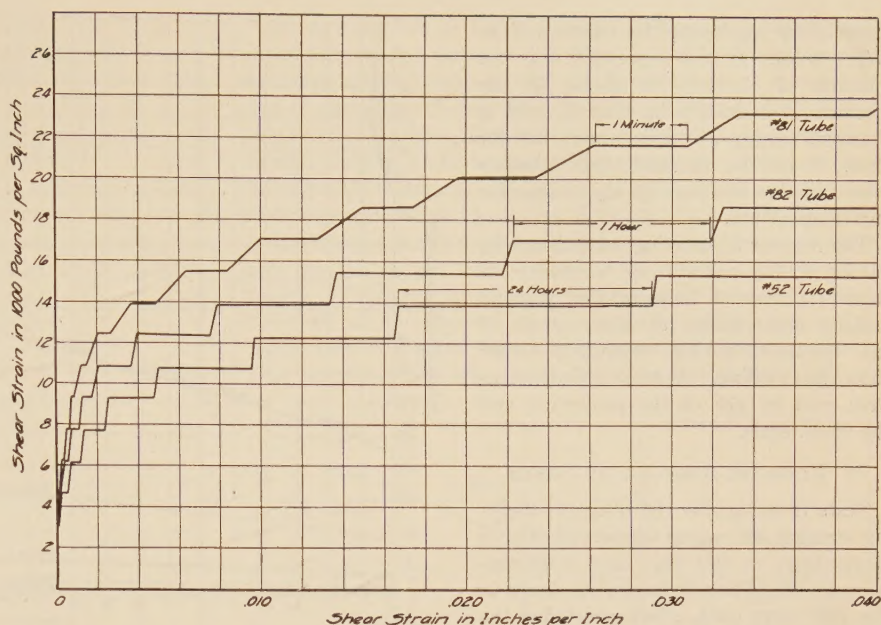


FIG. 12 EFFECT OF VARIOUS RATES OF LOADING AT 450 DEG. CENT.

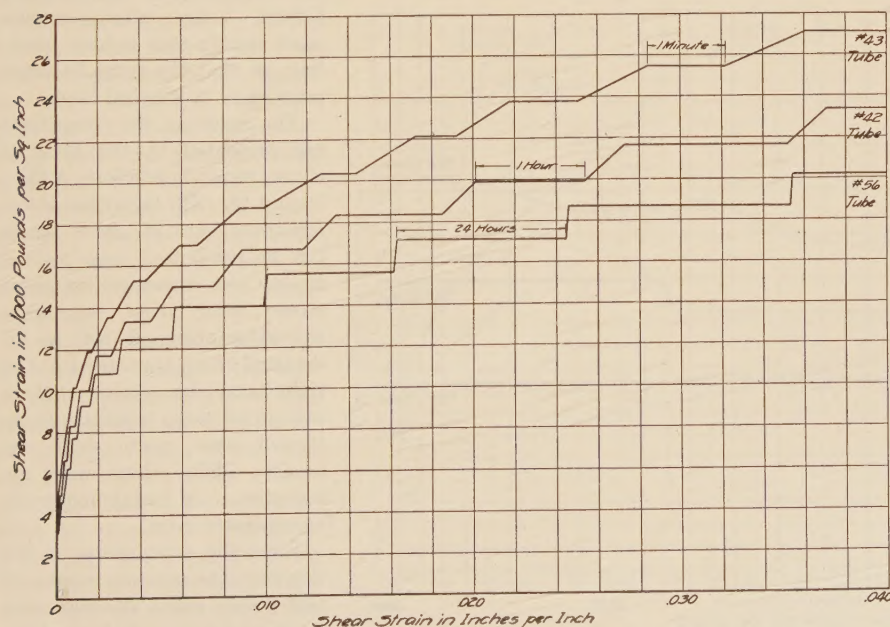


FIG. 11 EFFECT OF VARIOUS RATES OF LOADING AT 400 DEG. CENT.

material by employing the relation: $G = E/2(1 + \mu)$. In this expression G is the modulus of elasticity in shear; E the modulus of elasticity in tension, and μ Poisson's ratio, which is about 0.3 for steel. It can be assumed that Poisson's ratio remains constant at this value for any temperature.

The manner of arriving at satisfactory values of the modulus of elasticity in shear at elevated temperatures was by making observations of shear strain of the specimen during unloading rather than upon loading. Angular deformations were read by use of the projectors and the 96-in. scale.

4 ULTIMATE STRENGTH IN SHEAR

Tests to determine the ultimate shearing strength at various temperatures from atmospheric to 500 deg. cent. were conducted. Short-length specimens shown in Fig. 8(b) were used, which precluded the possibility of buckling. The results are given in Fig. 16 in the form of a curve.

In loading the specimens to determine ultimate shearing strength, increments of 10 lb., and in the latter part of the test, 5 lb., were used. The rate of application of the loads was particularly important in these experiments, and a rate of 10 lb. (1600 lb. per sq. in.) per 30 sec. was carefully observed.

This curve does not look like those usually obtained for ultimate strength in tension at different temperatures. One of the reasons for the appearance of the curves in tension may be the complicated condition caused by necking. This situation is not present in experiments in uniformly pure shear produced by torsion. More experiments are required.

IV—LONG-DURATION TESTS AT HIGH TEMPERATURE

1 RESULTS OF LONG-DURATION TESTS

Long-duration creep tests of tubular specimens of medium-

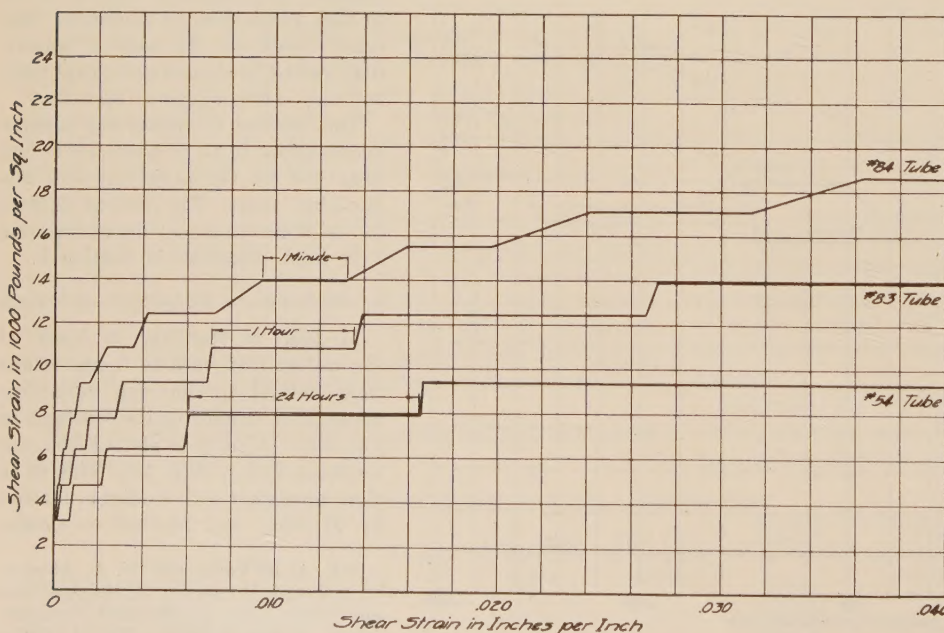


FIG. 13 EFFECT OF VARIOUS RATES OF LOADING AT 500 DEG. CENT.

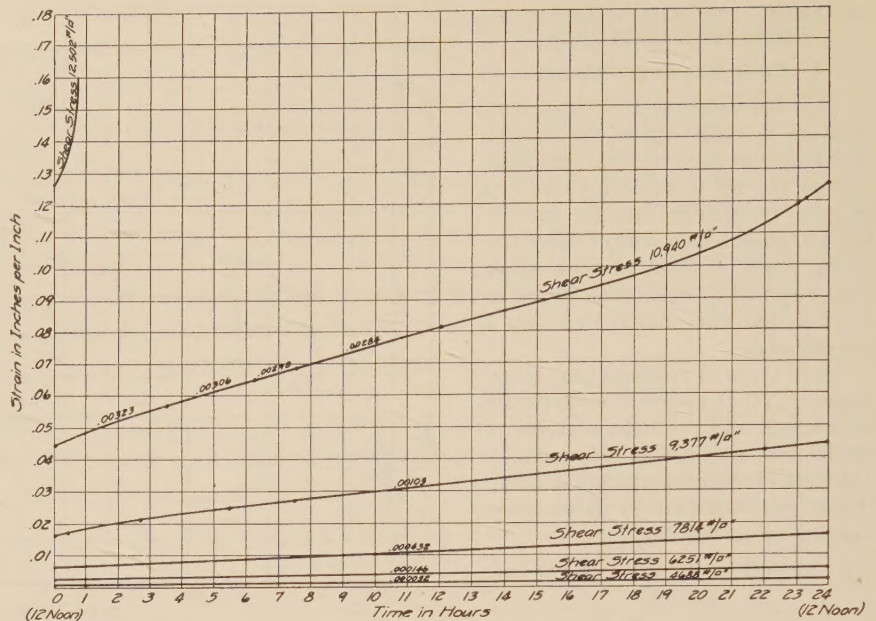


FIG. 14 CREEP RATE BETWEEN 24-HOUR LOADINGS AT 500 DEG. CENT.

carbon steel subjected to uniformly pure shear were made at temperatures of 400 and 500 deg. cent.

A number of the creep tests in shear were conducted in the usual manner, that is, the specimen was brought to the required temperature and the stress increased to a predetermined value, after which strain measurements were observed at certain time intervals. It was noted that the minimum rate of creep in each instance occurred at approximately the same total shear strain, and that buckling of the tube took place soon afterward. Strain, then, appeared in these cases to be the criterion of minimum rate of creep and also of buckling failure. Fig. 17 gives a family of time-deflection creep curves of the usual type of test made at 400 deg. cent. It is clearly seen from the first four curves that the minimum rate of creep occurs in each case at about 0.10 shear strain. The sharp upward turn in the curves denotes the initial stage of buckling failure. Large deflections take place during this sudden buckling, so that the curve becomes practically a vertical line.

The results of the creep tests are presented in the form of curves shown in full lines in Figs. 18 and 19. The logarithm of the minimum rate of shear strain per 24 hours has been plotted against the corresponding shear stress. Each point represents the value obtained from an individual creep test noted at the right-hand edge. Some of these individual creep experiments extended over more than one month, while others were accomplished in about one week, as explained later.

From the experiments at 400 deg. cent. the generous number of test points which describe such an unmistakable path leave little doubt as to the character of

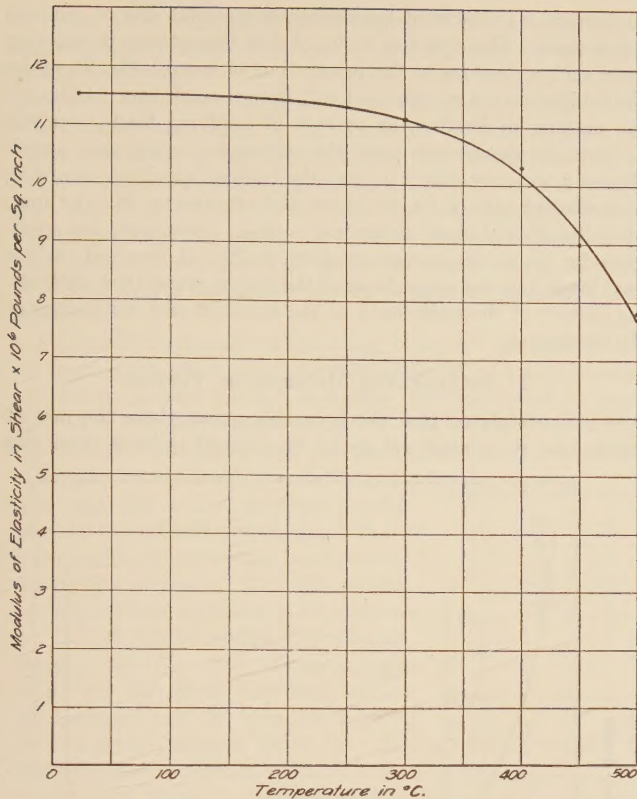


FIG. 15 MODULUS OF ELASTICITY IN SHEAR OF 0.34C STEEL AT VARIOUS TEMPERATURES

creep in shear of this material. The similar trend of the curve at 500 deg. cent. is established with reasonable assurance. Over a large portion of the curve for higher rates of creep the points fall in a straight line, but at lower rates there is a marked decrease in the creep rate for decreasing shear stress. In no creep tests has creep ceased. It is hazardous to predict beyond experimental evidence, but it appears that although there is a decided drop in the creep rate at the smaller stresses, delicate instruments which are furnished by this present method and further investigation of the problem may reveal the existence of creep very much beyond the range that has hitherto been supposed. The curve may even be asymptotic to the axis of the abscissa. Further experiments are in progress at present to establish more data for these low rates.

It may be reasoned that at the upper end of the curve very high rates of creep may be produced by large shear stresses. A physical maximum shear stress may well exist which causes instantaneous failure or, better, an infinite rate of creep. This stress is probably in the neighborhood of ultimate shearing strength, and so it seems the upper part of the curve becomes asymptotic to this practical limiting shear stress.

It was stated above that the values of the points which designated the shape of the curves of Figs. 18 and 19 represented the minimum rates of creep. From all of the tests made, a constant rate of creep has not been observed over any appreciable period of time, but rather a decreasing, or, in the case of approaching buckling failure, an increasing rate of creep. Fig. 20 is a typical curve which illustrates this point. These curves are obtained from any creep test by merely dividing the amount of shear strain which has taken place during an interval between readings by the length of the interval in hours, usually about twelve. There are three quite distinct parts of such a curve. The first portion, denoted by (a), is characterized by a rapidly falling rate. In some tests this occurs comparatively quickly. This part is followed by a region (b) of very much more uniform

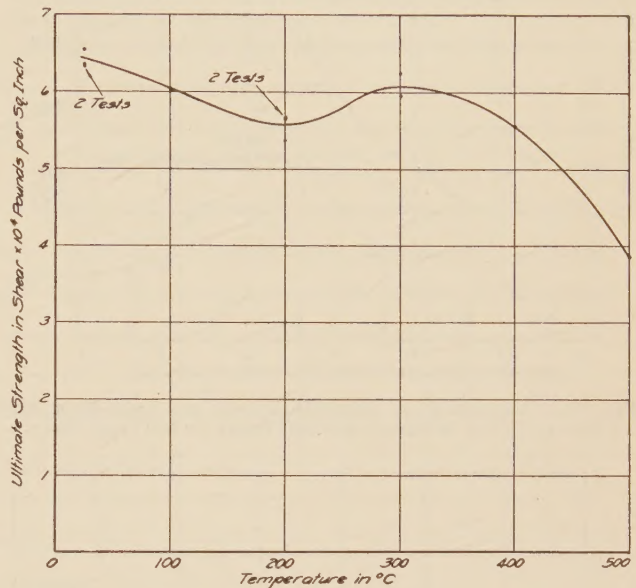


FIG. 16 ULTIMATE STRENGTH IN SHEAR OF 0.34C STEEL AT VARIOUS TEMPERATURES

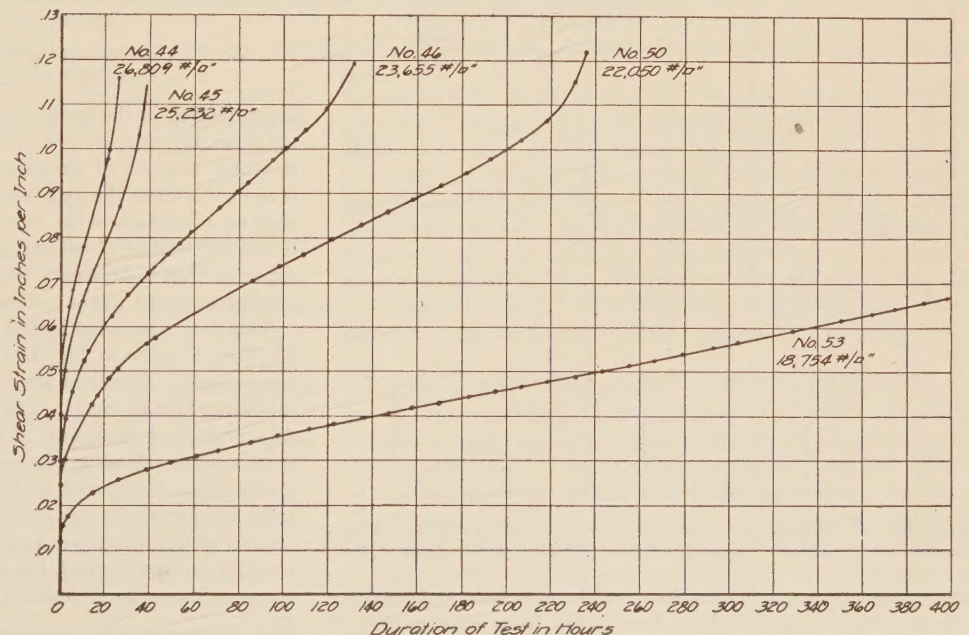


FIG. 17 SHEAR STRAIN VS. DURATION OF CREEP TEST FOR VARIOUS AMOUNTS OF SHEAR STRESS AT 400 DEG. CENT.

rate of creep, but all observations indicate it is not constant. The last stage (c) precedes buckling of the tube and shows a very sudden increase in rate. It can be conceived for practical purposes that the middle zone may be considered to be one of con-

to procure specimens of homogeneous material and of uniform dimensions. This was felt to be of first importance in entering upon such a program as the present one of creep. Fig. 21 shows the loading curves for five randomly chosen specimens. Although the manner of loading, as to rate of applying loads, was felt to be of no significance upon the subsequent creep test, nevertheless it was customary to load the tubular specimen according to a selected rate of 10 lb. (about 1600 lb. per sq. in.) per min. until the desired shear stress was acting. As is seen, the specimens for which the curves are given in Fig. 21 received various final loads, but the coincidence of the curves presents an interesting picture of the uniformity of the material and dimensions of the specimens.

2 ACCELERATED METHODS OF TESTING

It was postulated that the favorable point where the rate of strain was at a minimum could be reached quicker than was

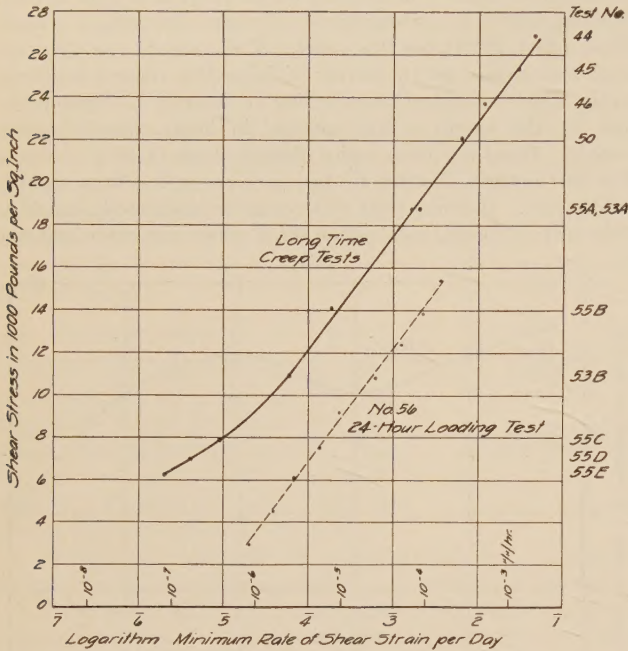


FIG. 18 COMPARISON OF SHORT-DURATION AND LONG-DURATION TESTS OF CREEP IN SHEAR OF 0.34C STEEL AT 400 DEG. CENT.

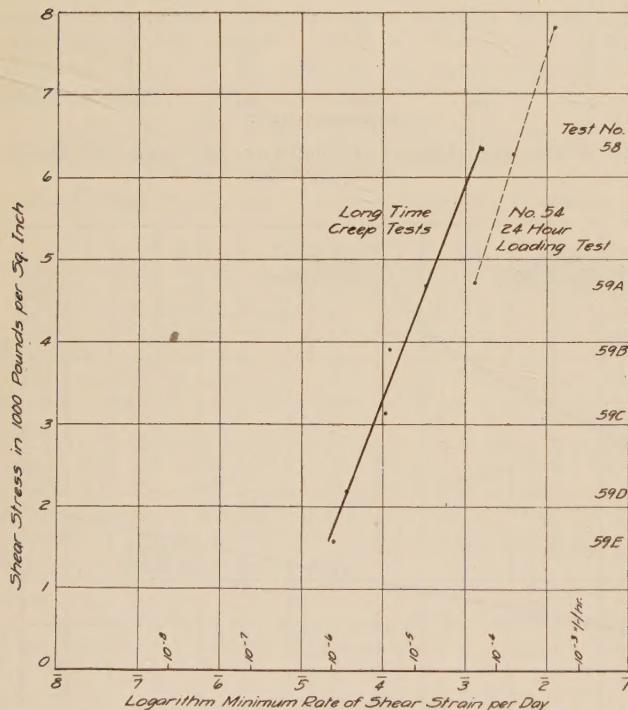


FIG. 19 COMPARISON OF SHORT-DURATION AND LONG-DURATION TESTS OF CREEP IN SHEAR OF 0.34C STEEL AT 500 DEG. CENT.

stant rate of creep. The values which have been obtained for plotting Figs. 18 and 19 have been taken from some portion of this (b) stage.

Mention was made earlier of the care which had been exercised

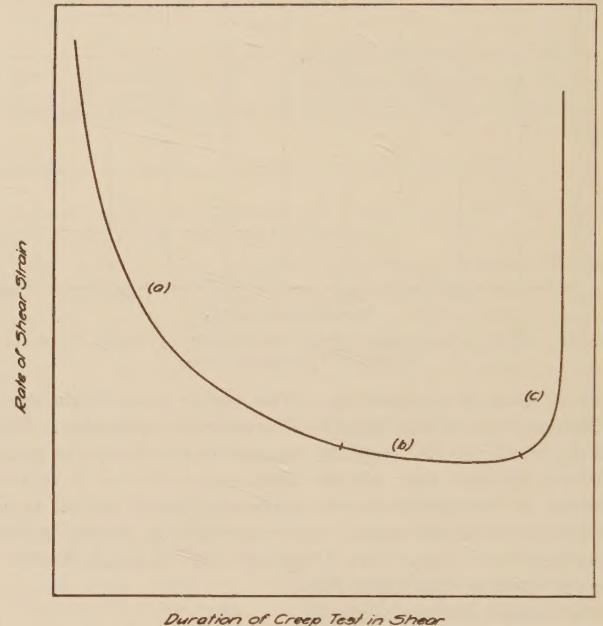


FIG. 20 CHARACTERISTIC CURVE OF RATE OF SHEAR STRAIN VS. DURATION OF CREEP TEST IN SHEAR

accomplished in the tests shown in Fig. 17, without affecting the value of this rate, by first overstressing the specimen. When a desirable amount of shearing strain had been obtained, about 0.08 in this case, the load would be reduced and creep would be read as a function of the new stress as though the entire history of the test had been according to common practice. It would be expected that a short time would be required for the specimen to become adjusted to the reduced stress.

This plan was investigated by selecting first a test (Tube No. 53, Test A⁵) seen in Fig. 18 that had been previously begun in the accepted manner of loading and which was approaching the minimum rate of creep. The new specimen (Tube No. 55, Test A) was loaded according to the same method which had been standardized for all creep tests, but the amount of the initial stress imposed was such as to produce in a few hours nearly the same total strain as was obtained with the other specimen (Tube No. 53) at that time over a period of about two weeks. When this total strain was reached, the excess load was removed so that the stress in the tubes in each experiment was the same. The rate

⁵ Each tubular specimen was numbered, and when more than one test was made which employed the same specimen the experiments were designated by Test A, Test B, and so on.

of creep soon dropped in the accelerated test to values which approximated within experimental limits the rate of creep shown by the usual test.

So close was the agreement in the two tests that the points when plotted according to the logarithm of the minimum rate against shear stress nearly coincided. Fig. 18 may be referred to for comparison of the results seen as two adjacent test points. The procedure developed for this test was considered worth adopting for further tests. Two weeks only were saved in this case, but for lower values of stress, and consequently of strain, it is seen that a far greater saving of time is capable of being effected.

Furthermore, should we be willing to accept the premise that no appreciable effect upon the minimum rate of creep is caused by this accelerated method of loading, it is reasonable to expect that all of the creep data necessary to plot the curve of the logarithm of the minimum rate of creep against the corresponding stress can be obtained from a test of one specimen. The specimen would then be loaded and quickly strained to a point slightly below that for the minimum rate of creep. The load would be reduced then sufficiently to produce a rate of creep within the desired range. After the creep rate had been found for this stress, the load would be decreased and the new creep rate at this stress obtained, and so on. In this manner it seems likely that enough information could be secured within a period of several weeks or months to afford a reliable indication of the properties of the material.

Several tests of this kind have been made with apparent success, but further study is required to substantiate the degree of accuracy of this form of test procedure. The points for rates of creep of 10^{-4} shearing strain per hour, and less, in the experiments at 400 deg. cent. and all the tests at 500 deg. cent. were obtained in this manner. These data are represented by the curves plotted as stress against the corresponding logarithm of the minimum rate of creep for the particular temperature in Figs. 18 and 19.

V—SPECIAL PROBLEMS

1 INCREASE OF YIELD POINT BY CREEP AND RESTORATION OF ORIGINAL YIELD POINT BY ANNEALING

In order to investigate the effect of creep upon the physical properties in subsequent room-temperature tests, a tube (No. 56) which had already undergone considerable creep was studied. Following the test at 400 deg. cent., which was reported in Fig. 11, the specimen was unstressed and permitted to cool slowly in the furnace. At room temperature the tube was loaded in torsion until the yield point was reached at about 29,450 lb. per sq. in., and then unloaded. Then by annealing the tube at 900 deg. cent. in the usual manner, all effect of any previous cold working was removed. The tube was again tested at ordinary temperature in twist and the yield point observed to be about 24,950 lb. per sq. in. The respective curves are given in Fig. 22. From these experiments it is seen that the creep test at 400 deg. cent. caused an increase in the yield point of about 20 per cent, based on the usual tests at room temperature.

This phenomenon differs from what we know of room-temperature tests where yield point is increased only by large loading. This increase of yield point was produced by comparatively small loads. It is also significant that Hooke's law is maintained practically up to the value of the new yield point. Usually in cold working, the increased yield point is attended by a marked rounding off of the curve preceding the yield point.

From other tests on unused specimens in torsion at room temperatures, curves like the one shown in Fig. 22(b) have been obtained. The material, then, which was subjected to creep and later annealed, resembles the original condition of the steel.

2 NATURAL JARS AND VIBRATIONS

It was felt for some time that vibrations, and particularly jars produced in the building, caused dynamic in addition to the static loads applied to the specimen under torsion. Although all observations of suddenly high creep rates did not follow known jars,

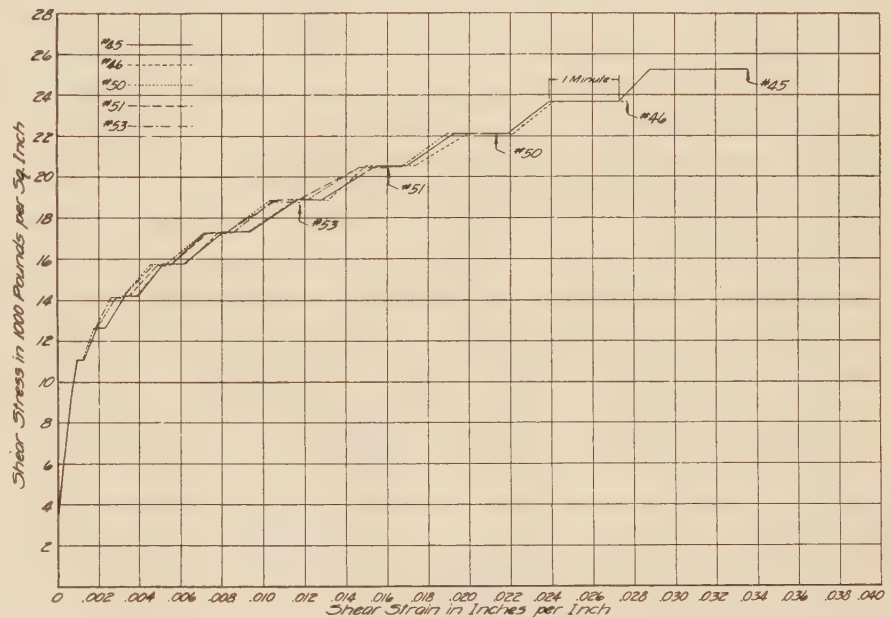


FIG. 21 LOADING CURVES FOR TUBULAR SPECIMENS AT 400 DEG. CENT.

these higher values were observed when jars were known to have occurred. During the assembly of heavy apparatus in a nearby room very erratic rates of creep were observed.

In normal times, rates were usually alternately high and low in reference to a smooth curve. In analyzing this condition it was discovered that the reading taken in the morning was the lower one and the evening reading the higher. Observations were recorded twice daily. This appeared consistent, since more jars, however small, were produced during the day, which resulted in the greater rate of creep observed at the evening reading.

A more detailed study was made over a four-hour period one evening when jars and vibrations were at a minimum. Readings of creep were recorded at five-minute intervals on two specimens (Nos. 53 and 55). Reference to the curves of Fig. 23 is suggested.

No creep was observed for the first hour and a half in the specimen whose average rate was about 3×10^{-6} shearing strain per hour until the observer unintentionally caused a sudden jar across the room. This jar resulted in an apparently instantaneous large creep, after which no further change was observed in the remaining two and a half hours. Rates of the order of 4×10^{-7} strain were observed without difficulty, and form the least count for plotting the curve.

The second specimen, whose average rate of creep was slightly greater, about 8×10^{-6} shearing strain per hour, showed alternate stages of creep and of no creep. When the small jar reported above was produced, these observations also showed that a considerable movement had taken place.

It is interesting to note that there is quite an obvious average rate of creep noticeable in the case of the upper curve of Fig. 23. Just before the sudden creep, the specimen is apparently strained less than the average amount, which prepares it particularly well for the occurrence which follows. The jar, then, not only brings the strain up to the "average rate line," but causes excess straining which results in a slowing up in the rate. The period which follows appears to indicate that the material tends to maintain an average rate of creep.

From these experiments it would be concluded that creep is a discontinuous process. Whereas creep is generally read as being continuous, it is probably in reality stepwise in nature.

A special apparatus has been constructed which is designed to make a photographic record of creep by directing a small spot of light on to the mirror of the measuring device. The beam is then reflected back on to a film on a drum turned by clock-work.

It is proposed later to make a study of the effect of intentionally applied pulsations. A light motor with a small eccentric load to cause vibrations will be placed on the load pan. This study is designed to reproduce qualitatively the conditions encountered

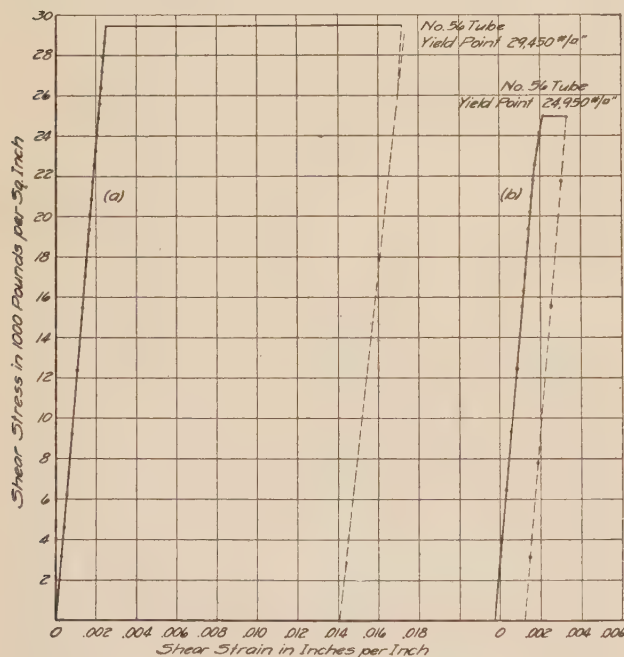


FIG. 22 TORSION TESTS AT 26 DEG. CENT.: (a) AFTER CREEP TEST; (b) AFTER SUBSEQUENT ANNEALING

in power plants where pulsations are frequently imposed in addition to static stress and high temperature.

From the study of jars which has been made, it was decided to mount the torsion-test equipment on springs. Springs were chosen in such a way as to make the frequency of the system a very low one so that outside jars and vibrations would not produce disturbances upon the torsion apparatus. The machines were therefore suspended from above, as seen by reference to Fig. 2. This eliminated the trouble caused by jars and vibrations. The temperature fluctuation effect is discussed in the following article.

3 TEMPERATURE FLUCTUATIONS

We must anticipate variations in temperature throughout any experiment of the order of one degree centigrade above and below the desired amount. In tension tests we know that these fluctuations materially affect the sensitivity of the readings of creep. They are far less serious in the case of torsion, but it is worth while to study the magnitude of their effect. An increase in temperature results in an increase in both the polar moment of inertia and the length of the specimen, and a decrease in the modulus of elasticity in shear. The resistance of the specimen to shear, then, tends to increase with a larger polar moment of

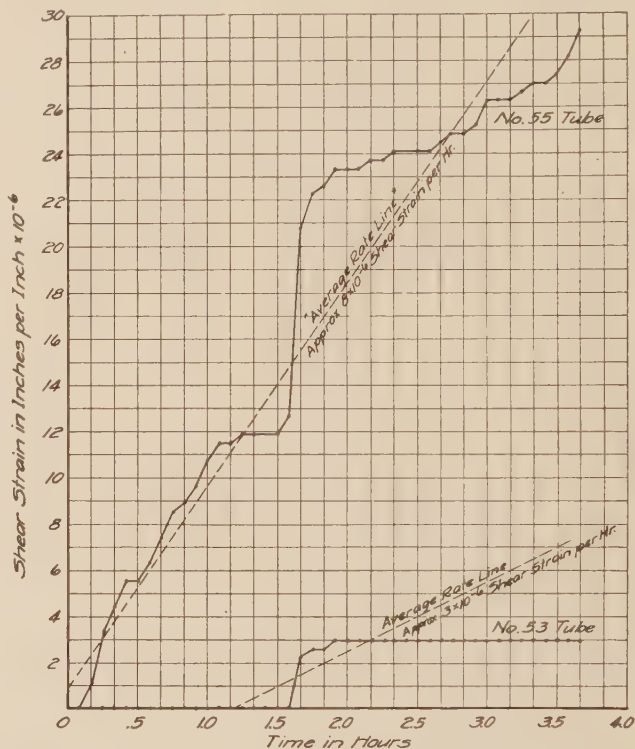


FIG. 23 CONTINUOUS RECORD OF CREEP FOR LOW RATES AT 400 DEG. CENT.

inertia, but shows a decrease with greater length and smaller modulus. The temperature effect upon modulus of elasticity in shear is very great compared with that upon the polar moment of inertia and the length. The ratio, in order, is about 150:5:1.25.

In the extreme case when the applied torque moment is large, the effect due to a two-degree-centigrade temperature fluctuation will be read as a shear strain of approximately 1×10^{-6} . With intervals of twelve hours between creep readings the effect of temperature fluctuations upon creep measurements amounts to rates of less than 1×10^{-7} shear strain per hour. The following calculations for an extreme particular case will help to make this evident.

Let:

θ = angle of twist in radians

t = 400 deg. cent., say, the desired temperature of specimen

$M_t = 1 \times 10^3$ in.-lb. = maximum torque moment

$L = 4$ in. = gage length at temperature t

$G = 1 \times 10^7$ lb. per sq. in. = modulus of elasticity in shear at temperature t

$I_p = 4 \times 10^{-2}$ = polar moment of inertia of tubular cross-section at temperature t

$c = 0.4375$ in. = mean radius of tube at temperature t

$\Delta\theta$ = difference in angle of twist in radians due to temperature change

α = 1.25×10^{-5} in. per in. = change per inch of L due to 1 deg. cent. temperature fluctuation at temperature t (coefficient of expansion)

β = 150×10^{-5} lb. per sq. in. = change per unit of G due to deg. cent. temperature fluctuation at temperature t (determined experimentally; this is discussed in Section III and an experimental curve is given in Fig. 15)

γ = $4 \times 1.25 \times 10^{-5}$ in.⁴ = change per unit of I_p due to 1 deg. cent. temperature fluctuation at temperature t

δ_s = shear strain in tubular specimen.

Then, due to a fluctuation of ± 1 deg. cent. from temperature t ,

$$\theta_t \pm 1^\circ \text{C.} = \frac{M_t L (1 \pm \alpha)}{G (1 \pm \beta) I_p (1 \pm \gamma)}$$

Therefore the difference in the angle of twist expressed in radians due to a 2-deg. cent. temperature change is, since α , β , and γ are small quantities,

$$\Delta\theta = \frac{2M_t L}{GI_p} (\alpha - \beta - \gamma)$$

and by substitution of the values for the symbols:

$$\Delta\theta = \frac{2 \cdot 1 \cdot 10^3 \cdot 4}{1 \cdot 10^7 \cdot 4 \cdot 10^{-2}} (1.25 \cdot 10^{-5} - [-150 \cdot 10^{-5}] - 5 \cdot 10^{-5})$$

so

$$\Delta\theta = 3 \times 10^{-5} \text{ radians}$$

Since

$$\delta_s = \frac{c \cdot \Delta\theta}{L}$$

Then, due to an angular deformation $\Delta\theta$ caused by a 2-deg. cent. temperature change, the resulting shear strain becomes

$$\delta_s = \frac{0.4375 \cdot 3 \cdot 10^{-5}}{4}$$

or

$$\delta_s = 3 \times 10^{-6} \text{ in. per in. strain}$$

When readings are made at 12-hour intervals, the effect of temperature fluctuations which will result in fluctuations in creep rate will be

$$\delta_s/\text{hr.} = \frac{3 \cdot 10^{-6}}{12}$$

or

$$\delta_s/\text{hr.} = 2.5 \times 10^{-7} \text{ strain per hour}$$

The figures in the results of these calculations have in several cases been rounded off to the nearest whole number. This latter value, then, represents the minimum reliable value which may be observed when temperature fluctuations of the specimen are in the order of ± 1 deg. cent. and all other conditions noted above regarding torque moment and dimensions are imposed. This temperature fluctuation registers its effect in changing the modulus of elasticity in shear, a polar moment of inertia, and the length.

It will be appreciated that as the torque is decreased, as is the case when small rates of creep are required, the magnitude of the effect due to temperature fluctuations is decreased in direct proportion. Rates of 1×10^{-8} strain per hour under such circumstances can readily be determined without difficulty when readings are made as frequently as 12 hours.

ACKNOWLEDGMENTS

Prof. S. Timoshenko conceived the importance and possibilities of investigating creep phenomena by uniformly pure shear, presented the problem to the author, and directed the entire program. To him credit is due for the vision and practical success of the project up to the present time. The author wishes to record his deep appreciation to Professor Timoshenko, moreover, for his personal interest and limitless encouragement.

To Prof. A. E. White and the Department of Engineering Research, of which he is director, the author wishes to indicate his appreciation for sympathetic interest in the problem, which included the assistance in the matter of personal expenses. The author also acknowledges with gratitude the generous support of the Department of Engineering Mechanics under the supervision of Prof. E. L. Eriksen, especially for the funds for the construction of the special equipment used in conducting the investigation.

